Acc Rec - 9 Mar 84

AD-A206 989

REPORT DOCUMENTATION PAGE

DTIC FILE COPY (2)

DTIC ELECTE APR 1 8 1989 S D

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release, distribution unlimited
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 89-0469
6a. NAME OF PERFORMING ORGANIZATION BROWN UNIVERSITY	6b. OFFICE SYMBOL (If applicable)
7a. NAME OF MONITORING ORGANIZATION AFOSR/NA	
6c. ADDRESS (City, State, and ZIP Code) Division of Applied Math 182 George St., Prov., RI 02912	7b. ADDRESS (City, State, and ZIP Code) Building 410 Bolling AFB, DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR	8b. OFFICE SYMBOL (If applicable) NA
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-87-0157	
8c. ADDRESS (City, State, and ZIP Code) Bldg. 410 Bolling AFB, DC 20332	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
61102F	2302	C2	

11. TITLE (Include Security Classification)

Impulsive Loading of Fiber-Reinforced Structures

12. PERSONAL AUTHOR(S)
Profs. Herbert Kolsky & Allen Pipkin

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 2/1/86 TO 12/31/88	89/3/1	22

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	impact, plastic waves, strain rate effect, structural response. (JES)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The work described concerns the response of metallic composite beams and simple structures to rapid dynamic loading. It has been shown experimentally that the observed plastic response of clamped beam specimens to very sharp transverse blows could be adequately described by the idealised theory formulated by Spencer and his colleagues so long as the duration was sufficiently short for the plastic wave not to reach the clamp. The reflection process for real clamping conditions was found to be very much more complex. The effects of blows of much longer durations on beams and portal arches are also described, as well as the effects of rate-of strain on the yield point of the matrix metal.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
Spencer T. Wu	(202) 767-6962	AFOSR/NA

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

AFOSR-TR- 89-0469

AFOSR-87-0157

FINAL REPORT ON GRANT AFOSR-87057 ON PROJECT ENTITLED 'IMPULSIVE LOADING OF FIBER-REINFORCED STRUCTURES'.

(Principal investigators Herbert Kolsky and Allen C. Pipkin
Division of Applied Mathematics Brown University).

This grant has supported a study of the dynamic, mechanical response of specimens of metallic, fiber-reinforced composites. Much of the work carried out has been experimental, and the program of testing was designed to see how well a comparitively simple mechanical model could be used to predict, with a reasonable degree of accuracy, the dynamic response of simple structures made of such materials. The types of rapid dynamic loading employed, namely impacts from fast moving hammers and explosive loading were chosen as being similar to those which might occur in practical engineering situations.

Most of the tests were carried out on cantilever specimens; these were fabricated in the laboratory, and were made by embedding thin steel piano wires in parallel arrays in a lead-tin alloy matrix. Some composite plate specimens were also prepared; this was done either by embedding a batch of wires arrayed in random directions in matrices of lead-tin alloy, or by using a sandwich structure comprising alternating sheets of thin steel foil and thin layers of lead-tin alloy. Tests were also carried out on the effect of lateral impacts on portal frames which had been constructed of three composite cantilevers held together at the two corners with strong, light, metal joints.

The dynamic elastic response of such composite beam specimens has been studied earlier, [1]. It has been shown that elastic theory as

developed for, homogeneous, anisotropic beams described the observations accurately; the main difference between the observed elastic response of beams made of these composite materials and that of beams of the same geometrical shape but made of isotropic metals is that the correction for the shear effect in bending is very much greater for the anisotropic beams. When flexural plastic deformation occured in composite beams, it was found that the plastic flow was entirely in the form of shear of the matrix metal, i.e. during plastic deformation the material behavior in the fiber direction was governed by the elastic tensile response of the steel wires, while the plastic yield was governed by the yield stress in shear of the metal matrix.

Now, the extent to which the response of the material approaches that of the simplified, idealised model of a fiber reinforced solid depends on how large the ratio E/G is compared to unity, E is here the extensional modulus in the fiber direction, and G is the effective shear modulus in the bending plane. For elastic deformations of these metal composites E/G is of the order of 5, while for plastic deformations E/G_1, where G_1 is the gradient of the strain-hardening curve in shear, it is of the order of 300. Thus for plastic deformations which are large compared with the yield strain, it is not unreasonable to model the material as an ideal fiber-reinforced solid. Such a solid is defined as one which is completely inextensible along its fiber directions. Plastic yield can take place in such a solid when it is loaded in a direction other than a fiber direction, the matrix metal then yields in shear: for such an

ideal material $E/G_1 \rightarrow \infty$. Furthermore, when the plastic shear deformations become large compared to the elastic shear deformation at yield, the use of a rigid-plastic treatment, rather than the more realistic elastic-plastic treatment, should not lead to large numerical errors in the predictions of the observed plastic strains.

For a very sharp blow applied transversely to a composite beam, Spencer [2] has treated the problem of the mechanical response in terms of the model of an ideal, infinitely long, rigid-plastic beam. When a transverse blow is applied to such a model beam, instead of the flexural plastic waves which would be propagated along an isotropic metal beam, plastic waves of shear travel along the composite beam. If further, it can be assumed that the strain hardening gradient is constant i.e. the strain hardening is linear, the plastic wavefront travels with a constant velocity along the beam, [thus, if the strain hardening gradient is G_1 the velocity of the plastic wave is $\sqrt{(G_1/p)}$]. Since the response of the composite is assumed to be rigid plastic, no elastic deformations take place, the velocity of elastic waves is infinitely great, and for the duration of the impact the region of material ahead of the traveling plastic wavefront is at the shear yield stress, of the composite τ_o.

The theory as outlined above was applied to a composite cantilever beam clamped at one end. The problem considered was to determine the effect of the transverse impact of a small mass travel at high velocity which hits the free end of the cantilever. As a result of the

impact, a plastic shear wave travels along the cantilever, and the mass is slowed down by the force exerted on it by the beam. If the mass is brought to rest before the plastic wavefront reaches the clamped end, all motion ceases, the length of beam affected is equal to the distance the plastic wavefront has traveled during the duration of the impact. If, however, the projectile has not been brought to rest in the transit time of the plastic wavefront, a reflection of the plastic wave at the clamp is assumed to take place. Spencer used the end condition that the entire cross section of the beam at the clamped end, remains at rest. If this assumption is made, the amplitude of the reflected wave can be determined from the stress-strain relation of the composite, and the subsequent distribution of strain can be calculated.

Experiments on metallic composite cantilvers were carried out by detonating small explosive charges behind small metal pellets which were in contact with the sides of the free ends of the cantilevers. These produced impact durations less than the transit times of shear plastic waves along the cantilever lengths. Examination of the specimens after the impacts, showed that both the distance of travel of the plastic wavefront along the cantilever, and the plastic deflection of the free end were in reasonable agreement with the Spencer treatment. However, in experiments in which the tips of cantilever specimens were hit by traveling hammers in a HYGE shock-testing machine, the impact durations were found to exceed the transit times of plastic waves. The high speed cine records of

these impacts showed that a plastic wave traveled along the cantilever, as predicted by Spencer, but the cine frames after the wavefront had reached the clamped end showed no evidence of a reflected wave, and when the specimen was examined after the impact no discontinuity indicating the final position of the wavefront could be seen. It was found, however, that the final deflection of the tip was in reasonable agreement with that predicted by the Spencer treatment. The absence of a sharp reflected wavefront is perhaps not altogether surprising, since although the faces of the cantilever ends were tightly clamped, it is improbable that motion in the interior of the beam would completely cease at the clamped cross section.

The comparatively soft matrix metal could not be expected to hold the very much stiffer reinforcing steel wires in position, and some test experiments were carried out to study the nature of the reflection process further. Longer composite beams were firmly clamped at their central portions, so that each beam consisted of three sections: a clamped central section and two cantilever sections protruding from the two edges of the clamp. A sharp blow was then applied to the tip of one of the protruding cantilever sections by a fast traveling hammer in the HYGE shock testing machine. A plastic shock wave traveled along the beam and reached the clamp, where if complete clamping is assumed, all motion should cease, and no wave should travel through the clamp to the other protruding cantilever section. To see if this were so, strain gages were attached to the surface of this second cantilever section, it was found that however tightly the central section was clamped, a wave propagated in this second

cantilever section. This would appear to indicate that if reflection does take place, it is not sharp, and that any reflected wave is highly distorted. The output of strain gages mounted on the cantilever section which was hit confirmed this, in that they showed no evidence of a reflected wave-front.

The fact that the final plastic displacement of the cantilever tip is in reasonable agreement with the theoretical predictions based on the model of a sharp reflection may be accounted for heuristically, by the fact that whatever assumptions are made about end conditions, the kinetic energy communicated to the beam by the impact is the same, and the fraction of that energy which is converted into plastic work will also, be approximately the same. The whole question of the stress distribution in the neighborhood of the clamped end of a bent beam is one of some complexity, even in the case of the elastic bending of an isotropic elastic cantilever since it is impossible uniquely to formulate exact end conditions which are realizable in practice. For elastic cantilevers of materials which are not too highly anisotropic, the clamping results in distortions of the stress field which extend only one or two beam widths from the clamp, but with increasing anisotropy the length of this region of distortion increases and may well result in very complicated end conditions for a plastic wave approaching a nominally fixed clamp (cf[3]).

Experiments were also carried out on impacts of longer durations, where although the conditions were dynamic and some of the energy communicated by the impact appeared as kinetic energy of sections of the structure, (both translational and rotational), the times involved were

sufficiently long for wave propagation effects to be relatively unimportant. Thus during the duration of the impact, stress waves were able to traverse the dimensions of the sections many times, and the motion of the structure could be treated, as if it were made up of elements of lumped inertia each of which could move translationally or rotate about its center of gravity. One structure which was studied was that of a long metallic composite beam, the central section of which had been clamped; the set-up here was similar to that described earlier in the tests for seeing if a plastic wave penetrated a tight clamp. In the tests described now, however, the clamping was not so tight and a blow of long duration, (several tens of milliseconds), was applied transversely to the tip of one of the protruding cantilevers by hitting it with a very heavy fast traveling hammer. The subsequent history of the deformation was monitored by recording it with a high speed cine camera.

The first effect seen after the impact was the elastic bending of the cantilever section which had been hit, the rest of the beam stayed undisturbed. The next phenomenon was yield in shear of the central section, this immediately resulted in rotation of the second cantilever. Damped elastic oscillations of the system continued after the end of the impact. When the specimen was then examined, it was found that almost all the plastic deformation was in the form of a constant shear in the central section, the cantilever sections, which were at an angle on each side of it, showed no plastic flow. (cf.[4] and [5]).

More complicated structures, namely portal arches were constructed by mounting three composite beams as three sides of a square and clamping the two free ends in the HYGE shock testing machine. The three beams were held together at their corners by two light steel corner pieces which gripped the ends tightly. Impacts were produced by hitting either the center of one of the side cantilevers, or the center of the top one, with a heavy fast moving hammer. High speed cine records were taken of the impacts with a FASTAX high speed cine camera.

In attempting to analyse the mechanical response of such structures to sharp blows, and to define the distribution of residual plastic strain, a knowledge of the stress-strain response of the material of the structure, both in the elastic and the plastic range is required. The equations which are derived to determine the strain history depend also on the form of the yield conditions as well as on the initial conditions of the problem. These equations are often very complex, and it generally requires considerable computation to obtain numerical results. For engineering purposes, if the distribution of permanent plastic strain is all that is required, adequate numerical estimates can often be obtained more quickly by using rather drastic simplifying assumptions. One such approach is to assume that the material has a rigid-plastic response, this approach gives satisfactory predictions when the deformation takes place comparitively slowly, and when the final plastic strains are large in comparison with the elastic strains at yield.

For more rapid dynamic loading, where the structure acquires considerable kinetic energy by the time that yield first occurs, it is

found that the rigid plastic assumption can lead to large errors, and in order to obtain more accurate estimates, Symonds [6], has developed a method which he calls the Simplified Elastic-Plastic Technique. In this method the strain history is split up into elastic and plastic parts. Symonds has shown that the method gives predictions of the final plastic deformations which are far closer to reality than those obtained with the rigid plastic assumption. The predicted response for the impacts on composite portal frames has been determined by this technique by using the known mechanical response of the composite cantilevers, and the assumption that the beams yield when the shear stress reaches a critical value. Preliminary comparisons of the results of these calculations and the observed behavior have proved encouraging.

Now, the stress-strain behavior of the metal used as the matrix in the composites, namely lead tin alloy, is, like mild steel, highly strain-rate dependent. Thus the yield stress increases with the rate at which the metal is deformed. A series of stress-strain curves were obtained on a conventional testing machine at rates of deformation ranging from 3 x 10^{-4} per sec. to 30 per sec.. It was found that the elastic portions at all these rates were the same, the yield stress however, steadily increased as the rate of deformation increased. The yield points were all quite sharp and the portions of the stress-strain curves which correspond to plastic deformation were all approximately linear. The gradient of these plastic regions of the curves seemed to be independent of the rate of strain. Thus, the stress strain curves for increasing strain could be described as

bi-linear elastic behavior corresponding to stresses between zero and the yield stress σ_c, and linear strain hardening with a strain hardening coefficient σ_1, occuring beyond the yield point.

Thus, σ_c increases as the rate of strain is increased, while σ_1 is the same for all strain rates. Mild steel also exhibits a similar dependence of the value of the yield point on rate of strain, and Cowper and Symonds [7] showed that the experimental observations of Manjoine [8] of the response of steel in tension over a range of rates of strain could be accurately described by the empirical relation

$$\sigma' = \sigma_c [1 + (\varepsilon'/\varepsilon_0)^{1/n}),$$

σ is here the value of the tensile yield stress at the rate of strain ε', σ_c is the value of σ' at vanishingly low strain rate, ε_0 is the rate of strain at which σ' is equal to $2\sigma_c$ and n is an arbitrary constant . Cowper and Symonds found that n = 5, gave the best agreement with Manjoine's experimental results.

In subsequent years this empirical relation has been used successfully to describe the response of a number of metals and alloys, and it seemed worthwhile to see if it could be applied to the experimental results we had obtained for the lead tin alloy. We found that it gave an almost perfect fit if we put n equal to 5.5 over the five decades of rate of strain over which we had made observations. It therefore seemed quite safe to use it to extrapolate the value of σ_c for the somewhat higher rates of strain which occurred in the impact experiments.

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APPENDIX

In this section, a more detailed description of some of the experimental results, together with figures showing graphs and photographic records are presented.

RATE OF STRAIN EFFECT

As was mentioned in the main text, the stress-strain behavior of the lead tin alloy which wes the matrix in the metal composite, was sensitive to the rate at which the composite was strained. It was found that the value of τ, the yield value at a rate of strain in shear $\dot{\gamma}$, can be represented by an empirical relation of the Cowper-Symonds type. For this alloy, the closest fit was found to occur if the empirical constant n was chosen to be 5.5, thus the exponent 1/n is equal to 0.18 and the relation can be written as

$$\tau = \tau_0\{1 + (\dot{\gamma}/\dot{\gamma}_0)^{0.18}\}, \qquad \text{(A1)}$$

τ_0 is the shear yield value at vanishlingly low rate of strain, and $\dot{\gamma}_0$, is the rate of strain at which $\tau = 2\tau_0$. Figure 1 shows a series of measured stress-strain curves in shear, for a range of values of $\dot{\gamma}$. The closest fit was found to correspond to the values, $\tau_0 = 3.0$ and $\dot{\gamma}_0 = 170$. The graphs show how these curves compare with those based on these numerical predictions. These predicted curves were obtained on the asssumption that the yield stress τ has the value given by equation A1, that the yield point is sharp, and that the strain-hardening, which occurs for higher stresses is linear, and that the strain hardening gradient is a constant which does not vary with the strain rate.. It can be seen that so long as the range of strain considered is several times the value of the elastic strain at yield, the deviations between the experimental observations and those predicted by this model are not too great, It can also be seen that the more drastic assumption, made by Spencer, namely that the material can be represented by a rigid-plastic model, leads to considerably greater errors.

Based on this model, the effect of a sharp blow applied transversely to the tip of a metallic composite cantilever can be predicted. Relations can be derived for both the distance of travel of the plastic wavefront, and for the final deflection of the cantilever tip. Figures 2 and 3 compare the experimental results obtained from impact experiments with these theoretical predictions.

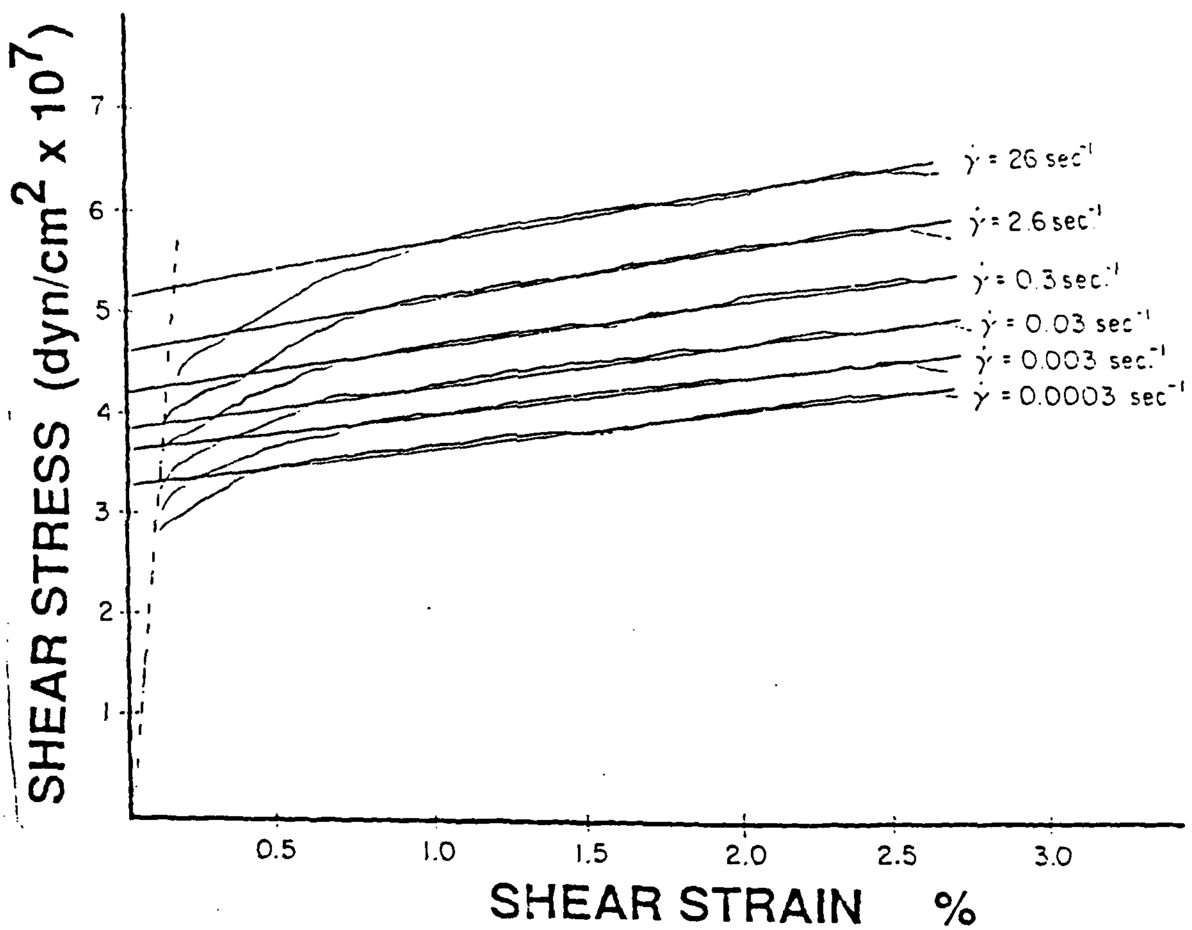
IMPACT ON LONG BEAM

In the main text, experiments were described, in which long beams were mounted so that their central sections were clamped, and two cantilever sections protruded from the two ends. A blow of sufficiently long duration for wave effects to be unimportant, was applied transversely to the tip of one of the cantilever sections; the general set up is illusrated in figure 4.. Observations of the subsequent motion were made with a high speed cine camera. Figure 5 shows the first 36 frames of the record; four selected frames are shown in figure 6; these illustrate different stages in the deformation. Finally, figure 7 shows still photographs of the final shapes of an impacted composite beam and an impacted aluminum beam of similar dimensions. The two beams were mounted similarly and subjected to similar impacts at the tips of the top cantilever sections. The difference in the final shapes of the aluminum and the composite beams is a result of the fact, that in bending, homogeneous metals yield at a critical value of the bending moment and the plastic deformation is confined to local plastic *hinges* , whereas in metallic composites such hinges cannot form, and yield takes place in the form of shearing of entire sections, (cf.figure 3)

IMPACTS OF COMPOSITE PORTAL FRAMES

Similar types of impact experiments have been carried out on composite portal frames. Each of these frames was made from three composite cantilever beams which were mounted in the form of an inverted U. The two free ends were clamped, and the three beams were held together at the two top corners by small steel corner pieces; the ends of the beams fitted tightly into these junction corner pieces. Impacts were applied to the frames in the Hyge testing machine, where heavy, fast-traveling hammers hit the center of one of the two vertical members of the frame. The deformation was monitored by taking a cine record of the impact, as well as by observing the electrical outputs of strain gages mounted on the three member beams. The first 28 frames of the cine record of the impact are shown in figure 8, and the shape of the specimen after the impact is shown in figure 9 It may be seen from the cine record that the impact produces considerable elastic deformation, and that the final shape shows that the frame is deformed into five linear sections, three of these were found to have undergone plastic yielding in shear.

COMPARISON OF EXPERIMENTAL STRESS-STRAIN MEASUREMENTS ON METAL COMPOSITE AND PREDICTED CURVES



COWPER-SYMONDS RELATION TAKES THE FORM:

$$\tau = 3.0\{ 1 + (\dot{\gamma}/170)^{0.18} \}$$

FIGURE 1

DISTANCE OF TRAVEL OF PLASTIC WAVEFRONT AS FUNCTION OF IMPULSE OF BLOW APPLIED

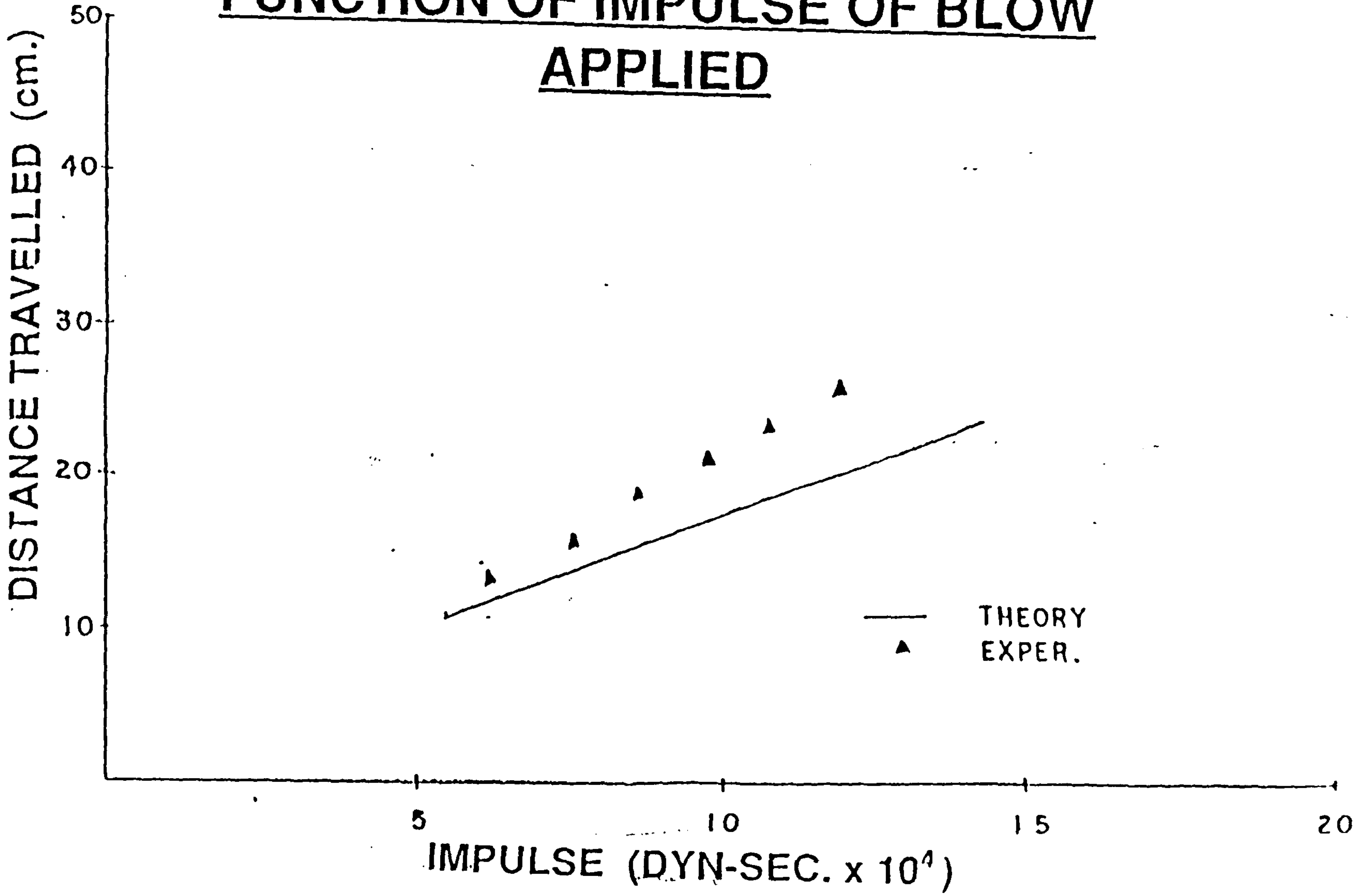


FIGURE 2

PLASTIC DEFLECTION OF CANTILEVER TIP AS FUNCTION OF IMPULSE OF BLOW

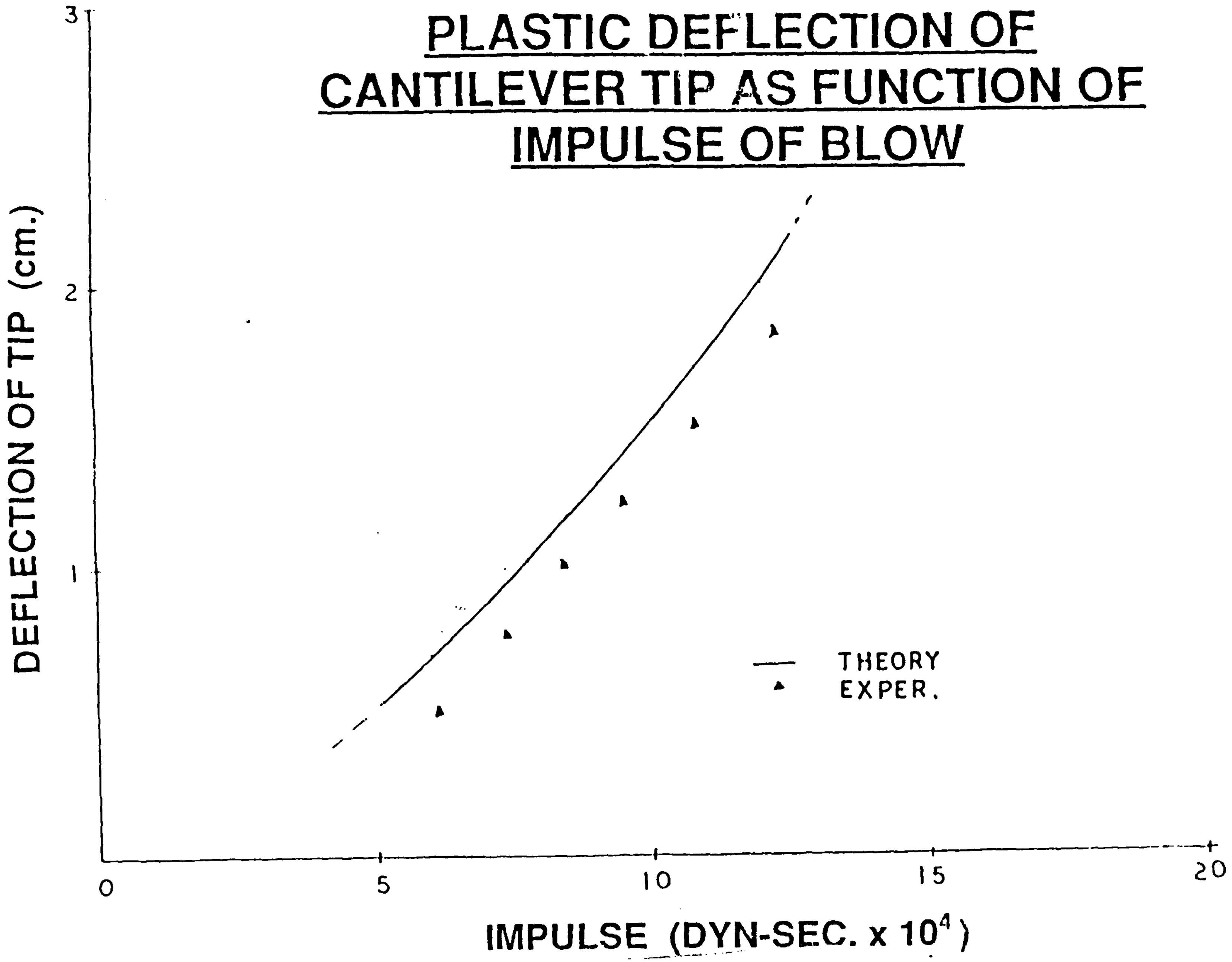


FIGURE 3

SET-UP FOR CLAMPED CANTILEVER

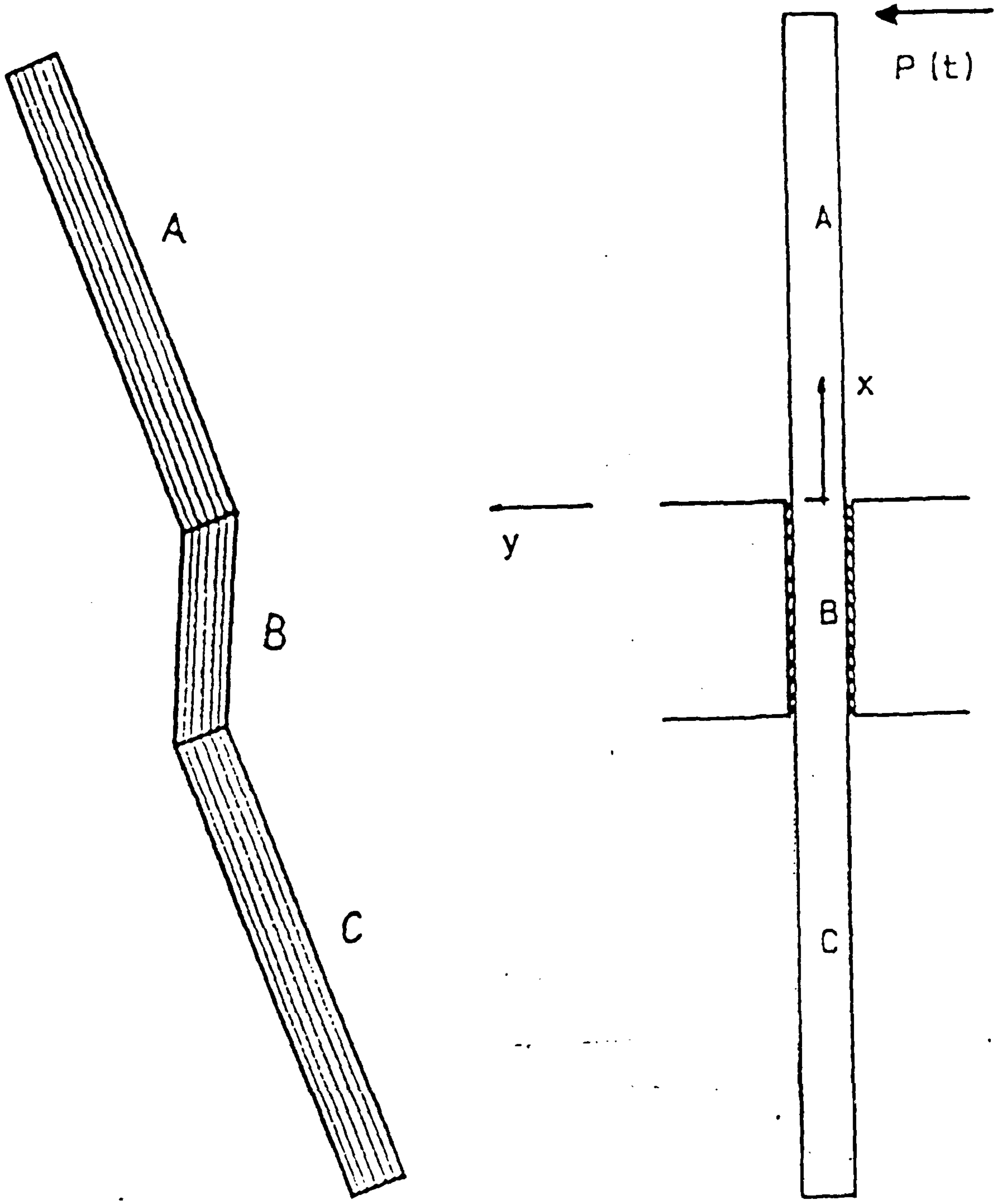


FIGURE 4

FIRST 36 FRAMES FROM CINE FILM OF IMPACT

(1300 FRAMES/SEC.)

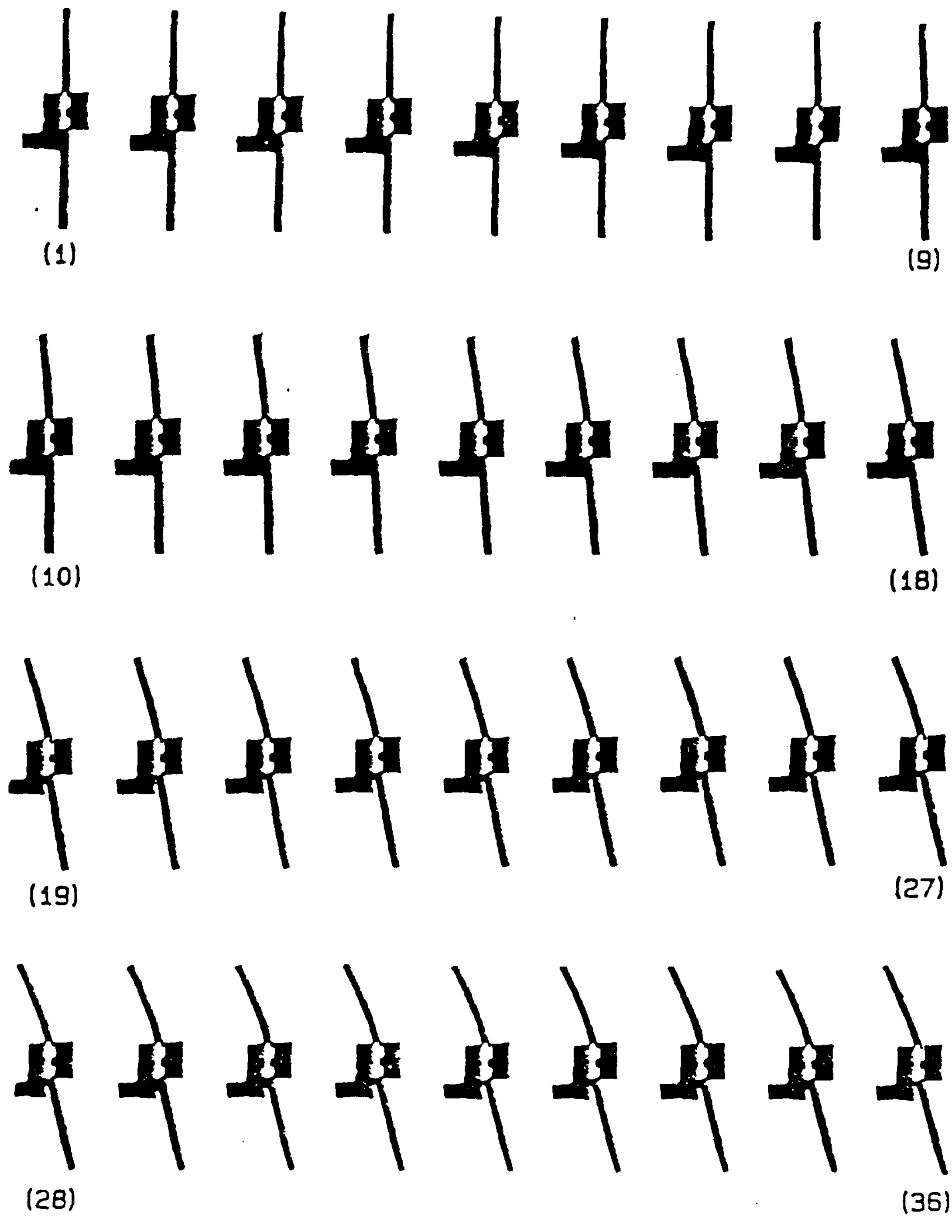
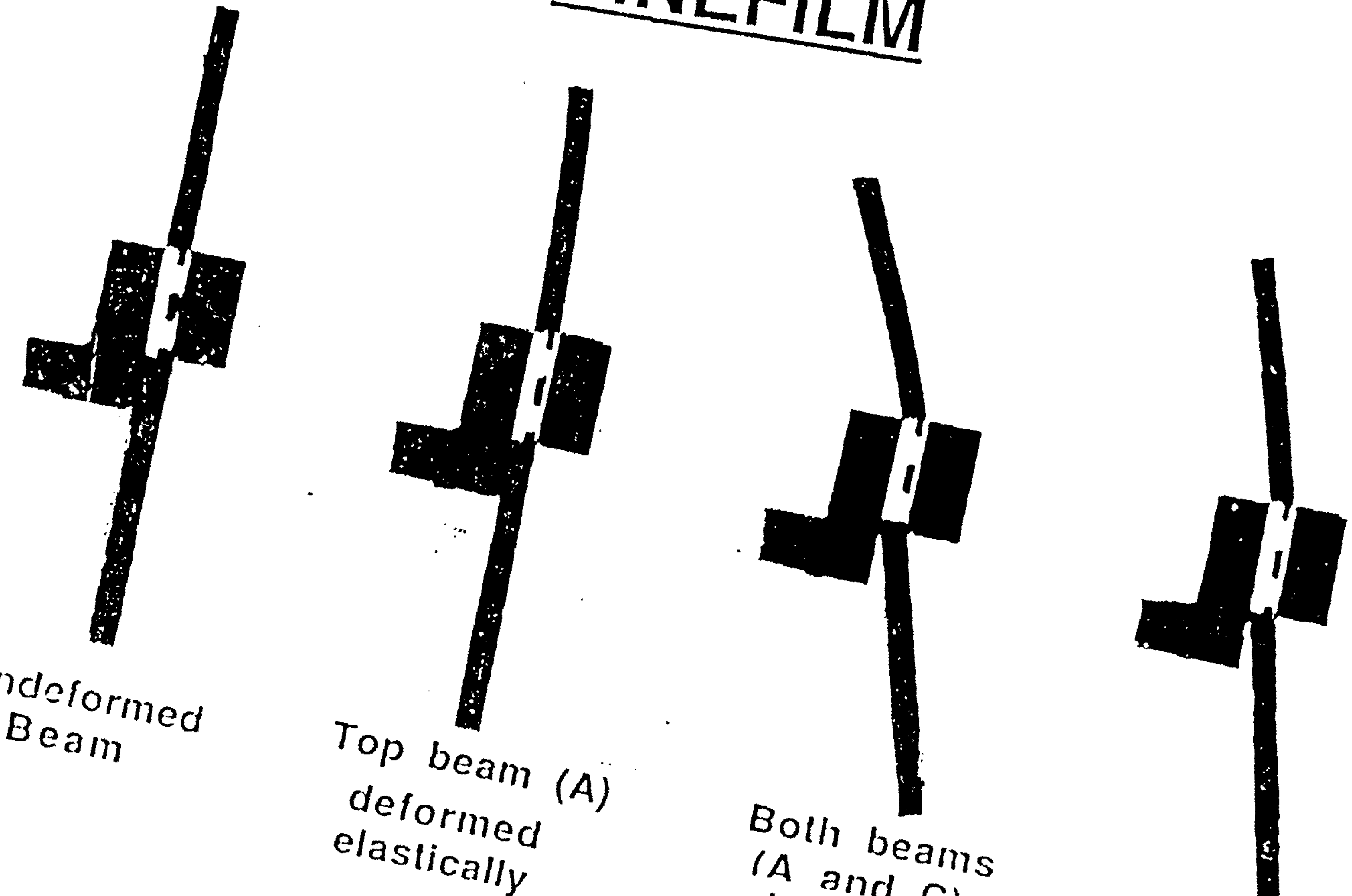


FIGURE 5

FOUR FRAMES FROM CINEFILM



Undeformed Beam

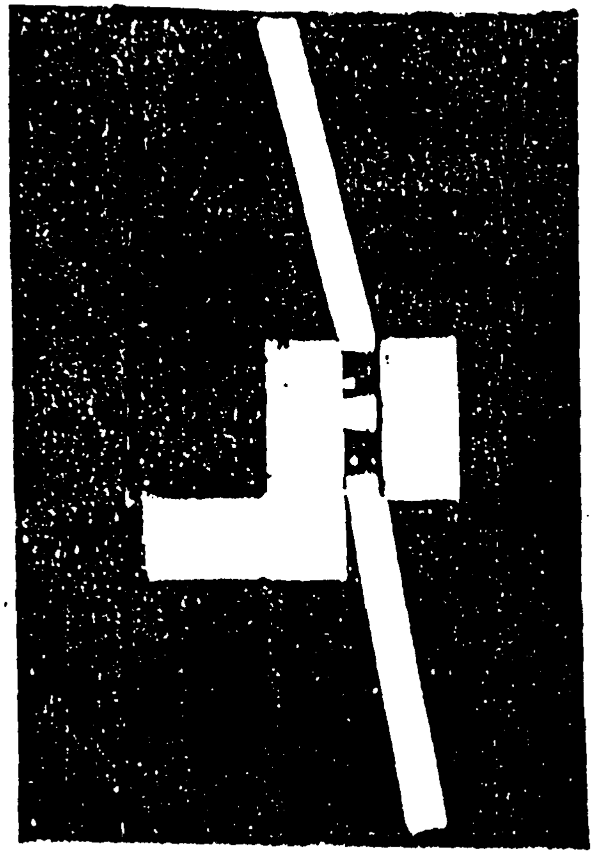
Top beam (A) deformed elastically

Both beams (A and C) deformed plastically

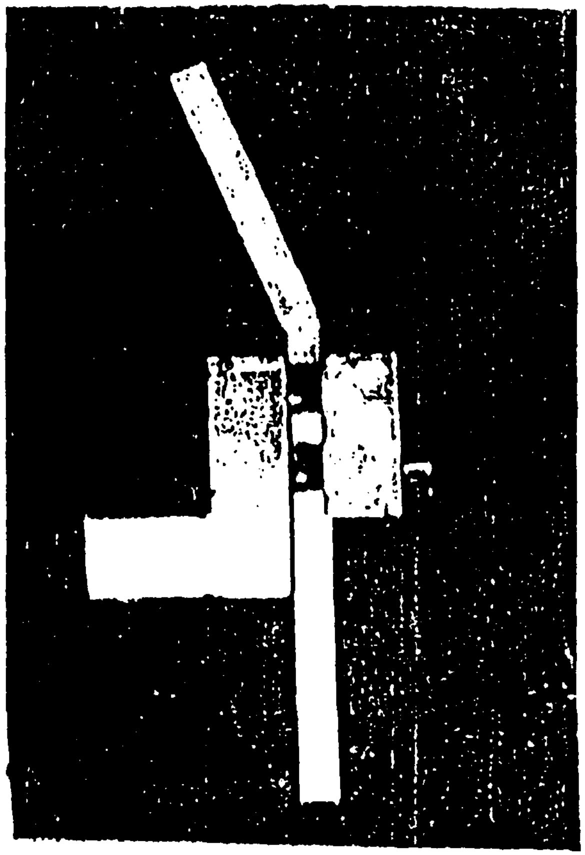
Final Shape

FIGURE 6

FINAL PLASTIC SHAPES OF COMPOSITE AND ISOTROPIC BEAMS

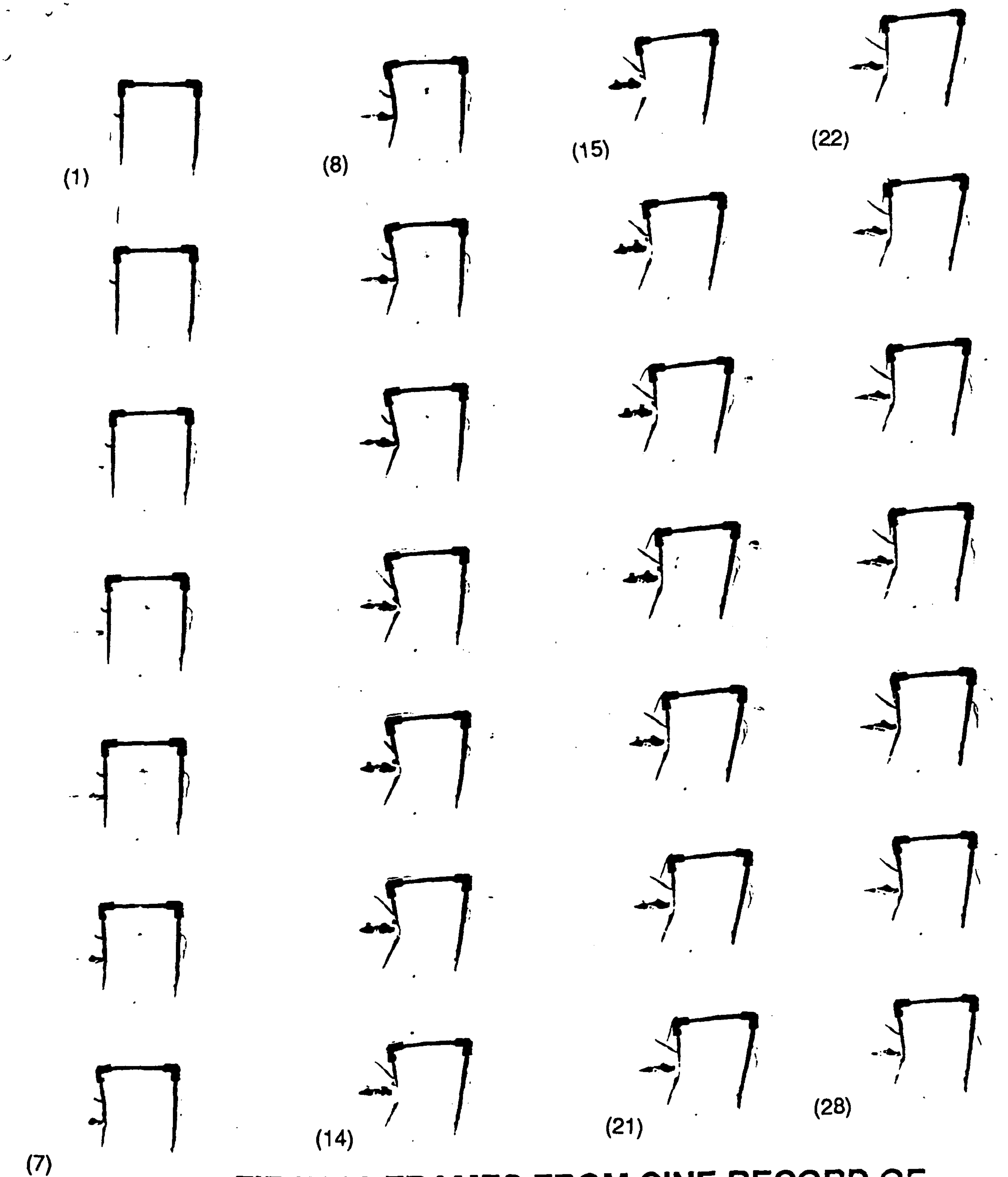


COMPOSITE BEAM



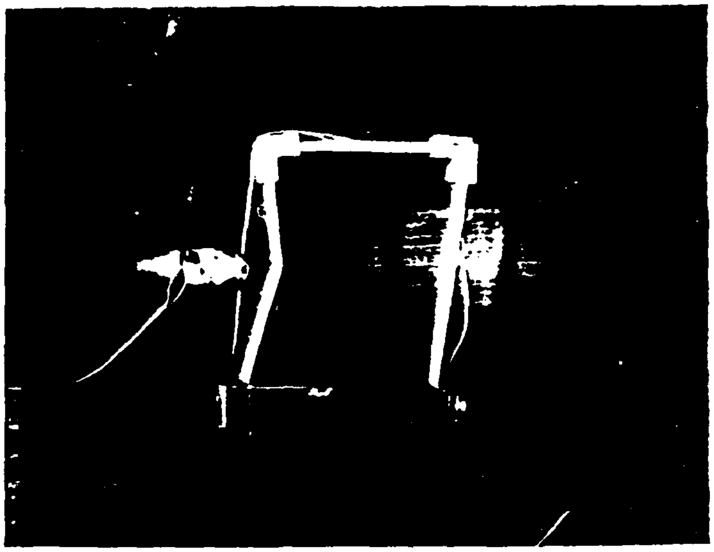
ALUMINUM BEAM

FIGURE 7



FIRST 28 FRAMES FROM CINE RECORD OF IMPACT ON COMPOSITE PORTAL FRAME (1350 FRAMES/SEC.)

FIGURE 8



FINAL SHAPE OF IMPACTED FRAME

FIGURE 9